Chapter 19. Radiation, Shielding and Collimation

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19.1. Radiation and Shielding

19.1.1. Introduction

This chapter explores how the Main Injector (MI) radiological issues will be affected with the Proton Driver (PD) as its injector. For simplicity, it is assumed that the PD will provide about 6.5 times more protons per hour than in the original MI design. [1] Data obtained from measurements and calculations are then scaled and compared to the MI design. Reasonable solutions are suggested, where possible, to mitigate the problem areas.

The current safety envelope for the MI and the original projected losses are given in Tables 19.1 and 19.2. [1,2]

Table 19.1 Main Injector Design Beam Intensities [2]

Description	Protons/hr During Operation	Type of Occupancy
MI-8 beam line	5.7×10^{16}	Unlimited
MI	5.7×10^{16}	Unlimited
P150 beam line: 8 GeV 120 GeV 150 GeV	 5.7×10^{16} 3.9×10^{16} 3.3×10^{16}	 Unlimited Unlimited Unlimited
A150 beam line: 150 GeV protons 150 GeV anti-protons	 3.3×10^{16} 3.3×10^{16}	 Unlimited Unlimited
F0 to AP1 beam line: 8 GeV 120 GeV	 2.9×10^{17} 3.9×10^{16}	 Minimal Minimal
Meson 120	3.9×10^{16}	Unlimited/Minimal
Recycler Ring (RR)*	1.5×10^{16}	Unlimited
MI-40 beam absorber: 150 GeV (protons/year)	 1.0×10^{19}	 Unlimited

* Number of protons or anti-protons in the RR will be administratively controlled to be less than 1.5×10^{16} per hour to allow access to the F0 region of Tevatron during a RR store.

Table 19.2. Projected Losses Based on the Current MI Design

Category	Energy	Protons	
Operational Losses	8 GeV 120 GeV	1.0×10^{19}/ year# 4.1×10^{18} / year	1.67×10^{15} / hr 6.83×10^{14} / hr
Accidental Losses	8 GeV 120 GeV	5.7×10^{16} / accident 8.5×10^{15} / accident	

We assume 1 year = 6000 operational hours

The radiological issues are ground water contamination, activated air emissions, residual activation in equipment and cooling water systems, and shielding.

19.1.2. Ground Water Contamination

Radiation leaking out of enclosures can induce radioactivity in the soil. Activated products will seep through the ground and reach the aquifer. Federal regulation limits the concentration of tritium in groundwater to less than 20 pCi/ml. There are regulatory limits on the other radioisotope levels, which could lower the above limit if present in the groundwater. However, other radioisotopes leach to a much lesser extent than tritium. Depending on many geological factors, the amount of radioactivity that reaches the ground water will be reduced due to dispersion and decay. Several important loss locations around the MI were chosen for geological characterization. Based on data obtained from these locations, a reduction factor was calculated for each area using a geological contaminant transport code. [3]

Table 19.3. Calculated Reduction Factors around the Main Injector

Location	Reduction factor due to seepage
MI-62	1.0×10^{-9}
MI-52	6.5×10^{-9}
MI-40	1.1×10^{-7}
MI-30	6.7×10^{-7}
MiniBooNE target area (vicinity of MI injection)	$< 9.7 \times 10^{-15}$

As shown in Table 19.3 the smallest reduction in the soil radioactivity is 6.7×10^{-7}, which is around MI-30. These results indicate that ground water contamination will not be an issue for the MI with PD intensities. There are limits on the concentration of radionuclides discharged to the surface waters as well, which should be considered for the sump discharges. However, the results of measurements of tritium concentrations in the sump samples from 17 locations around the MI, over the last few years, have shown no concentration levels above 0.1 pCi/ml. [4] Therefore, an upgrade to PD intensities would not cause a problem.

19.1.3. Activated Air Emissions

The level of radioactivity in the air is expressed in DAC (Derived Air Concentration). The DOE regulatory limit for allowed access into an area where radioactive air is present is 0.1 DAC. [5,6] Table 19.4 shows the PD era expected air activity obtained by scaling from measurements and the expected 2% beam loss at different MI locations.

Table 19.4. Calculated Radioactive Air Concentrations in the MI in PD Era

Expected beam extracted per hour	E (GeV)	DAC (current MI)	PD2 (DAC × 6)	PD2 DAC (1-hour delay)	PD2 DAC (2-hour delay)
5.70×10^{16}	8	0.33	2.01	0.14	0.02
3.90×10^{16}	120	1.74	10.46	0.74	0.08
3.30×10^{16}	150	1.74	10.46	0.74	0.08

Note the activity in the fourth column is immediately after the beam is turned off. More than 95% of the activity is from the ^{11}C and ^{13}N isotopes, which have half-lives of 20 minutes. and 10 mins, respectively. Imposing delays before entering these areas will be sufficient to meet the DOE requirement. Currently, the release of activated air from the MI is insignificant. During the PD era, measurements should be made to determine if additional sealing of air leakages is needed [7].

19.1.4. Residual Activity

Measurements on MI beam line equipment show that at some locations residual activity is above the predicted levels (Table 19.5).

The 622 kickers and the 100 kickers almost always show rates ranging from 20 - 50 mrem/hr. These are right next to their respective Lambertson magnet (MI-10 and MI-62), and dose rates from Lambertsons always dominate the area. If the loss rates scale linearly with the proton intensity, the extrapolated dose rates at some places are of the order of rem/hr. Radioactive decay curves for iron/steel show that most of the short lived isotopes decay within the first hour after irradiation. Waiting a few more hours would only lower the dose rates by a factor of two. If MI beam optics is not improved, access and repairs will become more difficult and time consuming.

The activity levels in the cooling system water will also increase with intensity and loss rate, which will require additional shielding, containment measures and reposting of the MI buildings where these systems are located.

Table 19.5. Residual Dose Rate History of the MI Components in mrem/hr at 1 ft, One Hour after Beam-Off [8]

Survey Date	MI10 LAM	Q105	Q109	Q112	Q113	Q114	Q313	321 LAM	MI40 LAM	MI52 LAM	MI62 LAM	Q626
2/21/2002	30	30	40	NR	50	NR	NR	400	40	150	100	NR
1/9/2002	60	NR	30	NR	40	NR	NR	125	20	150	150	20
11/18/2001	50	NR	NR	NR	NR	NR	NR	NR	NR	NR	60	20
10/7/2001	70	NR	NR	NR	NR	170	NR	100	40	200	100	25
7/10/2001	50	NR	NR	40	NR	NR	50	70	40	30	120	40
1/15/2001	50	NR	NR	NR	NR	NR	NR	60	30	20	50	60
11/6/2000	70	NR	NR	NR	NR	NR	NR	160	80	50	200	350
9/5/2000	150	NR	NR	NR	NR	NR	NR	100	100	50	70	130
7/5/2000	100	NR	NR	NR	NR	NR	NR	120	100	50	100	200
6/23/2000	200	NR	NR	NR	NR	NR	100	175	120	60	100	300
3/16/2000	150	NR	NR	NR	NR	NR	NR	150	100	45	25	20
2/23/2000	130	NR	NR	NR	NR	NR	NR	NR	100	50	NR	NR
2/7/2000	200	NR	NR	NR	NR	NR	NR	NR	NR	100	50	35
1/22/2000	500	NR	NR	NR	NR	NR	NR	300	150	200	75	90

(NR: < 20 mrem/hr or not surveyed)

19.1.5. Shielding

If the dose rates outside the shielding go up by a factor of six, there are generally two mitigation options available: [5]

(a) The design soil equivalent shielding thickness is about 24.5 ft. This is in accordance with the Preliminary Safety Analysis Report of the Main Injector. [1,2] However, the enclosure is built to support a soil weight of 26.5 ft, available for future MI intensity upgrades. Two extra feet of soil shielding provides about 5.2 times more attenuation, which would almost be sufficient to keep the current postings of the berms.

(b) Currently, most of the MI berms are classified as "Unlimited Occupancy"; the dose rate is less than 50 micro-rem/hr. A factor of 5 higher dose rate will make it a "Controlled Area", with limited occupancy. This means we have to add posting to the berms. There are a few places that will have higher radiation fields. These may have to be fenced and posted as a "Radiation Area"; the MI-8 service building may be such a place. Operational access procedures may have to change at places such as AP2 and the MI-8 cross over. This option is much less costly than option (a).

19.1.6. Shielding Conclusion

Use of the PD as an injector for the MI, will not significantly affect MI operations. As discussed above, most issues can be handled by revising operations, procedures and postings. Residual activity in the beamline equipment is the only issue that requires further R&D. No significant expenses are required in any of the mitigative options discussed.

19.2. Collimation

19.2.1. Requirements

The combination of a very high amount of Proton Driver beam power injected into the MI (~0.13 MW), tight MI aperture defined by the extraction and injection Lambertson magnets, as well as a complicated set of orbit bumps during the cycle, imposes serious constraints on beam losses. All eight MI straight sections are occupied by rf cavities, and injection and extraction systems. The horizontal orbit bumps used for a closed orbit displacement at the Lambertson magnet septa do not permit the installation of horizontal collimators close to the beam in the straight sections occupied by the extraction and injection systems. The only straight section that can be used for beam collimation is MI-30. Currently a kicker magnet is located at the center of MI-30 which is used both for beam extraction from the MI to the Recycler and injection from the Recycler to the MI. There is also a horizontal closed orbit bump (Figure 19.1), which is used for a kicked beam displacement reduction in the region from MI-22 to MI-32. To resolve this conflict the primary and secondary collimators will be retracted from the accelerator aperture in those cycles used for antiproton beam recycling.

Zero-dispersion at the straight sections of the accelerator complicates the problem further. This may require special measures such as “beam-in-gap-cleaning” (suggested for SNS) for off-momentum particle collimation.

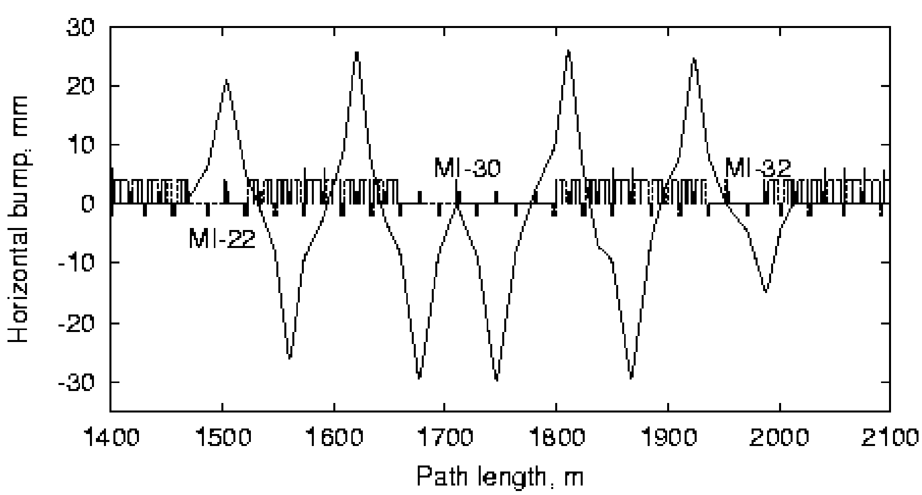

Figure 19.1. Horizontal closed orbit bump used for a kicked beam displacement reduction in the MI-30 section and beam displacement at the injection and extraction Lambertson magnets in the MI-22 and MI-32.

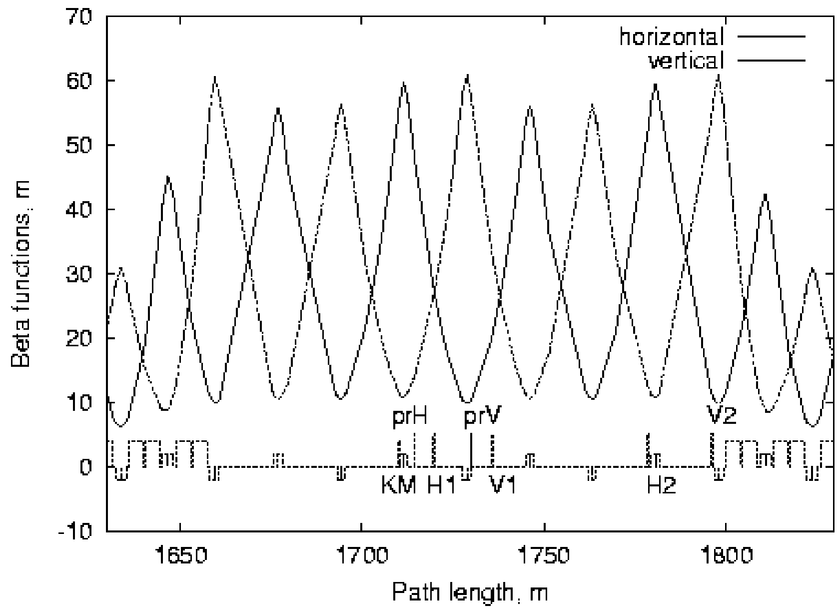

Figure 19.2. Beam collimation system location and beta function in the MI-30 straight section. PrH and PrV are primary collimators and H1, H2, V1 and V2 are secondary collimators.

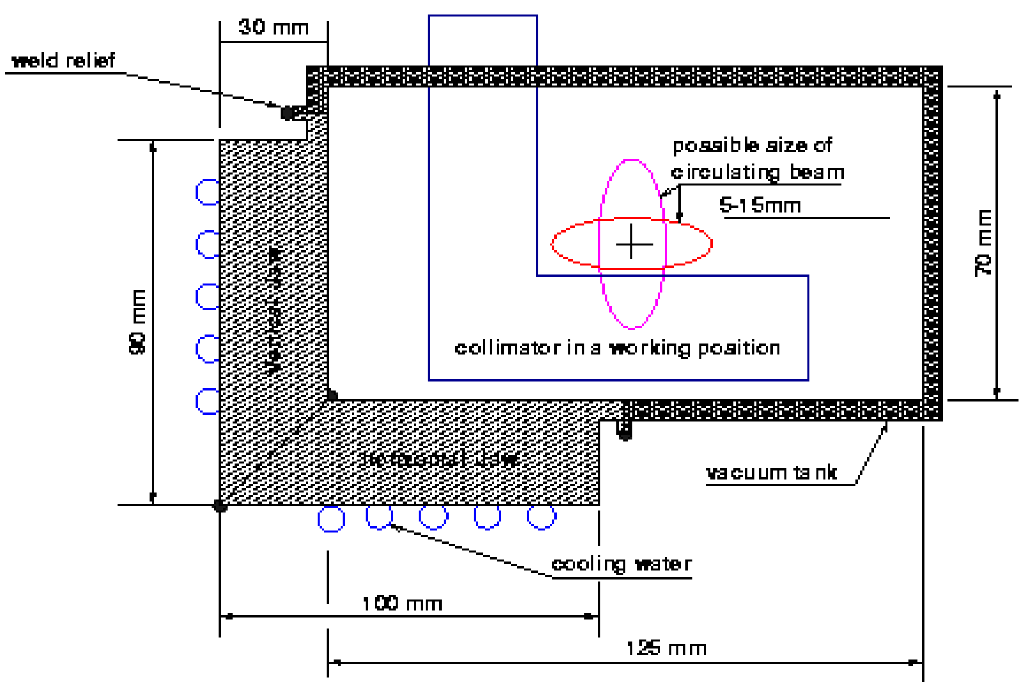

Figure 19.3. Secondary collimator cross-section.

19.2.2 Collimation System Parameters

A possible location for a two-stage collimation system is shown in Fig. 19.2. The system consists of one primary and two secondary collimators for both horizontal and vertical planes. Secondary collimators are located in an optimal phase advance location, downstream of the primary collimators. This provides for halo particle collimation at the secondary collimators during the first turn, after interaction with the primary collimator. Assuming that 1% of the beam is collimated at injection and 0.5% at the top energy, simulations show that most of the power is intercepted by the two secondary collimators (about 5 kW each). The total power intercepted is 11 kW. This requires local steel shielding ~1 m thick and ~2.5 m long, which covers the secondary collimators and the first quadrupole downstream.

The entire collimation system is concentrated in the downstream 2.5 periods of the MI-30 straight section. This leaves 1.5 periods for the electron cooling system and Recycler kicker magnet in a low radiation region upstream of the collimation system.

A system with collimators distributed around the accelerator at the necessary phase advance, in available free drift spaces, can be investigated. However, the required level of power interception by the collimators, makes this solution much more complicated and expensive.

The mechanical design of the secondary collimators and targets will be similar to those already built and installed in the Tevatron for Collider Run II. Those collimators consist of 2 pieces of stainless steel, 0.5 m long, welded together in an "L" configuration (Fig. 19.3). The collimator assembly is inside a stainless steel box with bellows at each end. Full range of motion is 50 mm, in steps as small as 25 μm if required, and a maximum speed of 2.5 mm/sec. Linear differential voltage transformers provide position read-backs. The primary collimator assembly is identical to the secondary collimator assembly, except that the target "L" blocks are only 0.1 m long. The 1 mm thick, machined-tungsten primary collimator jaws are bolted to the stainless steel blocks. The blocks provide a good heat sink for energy dissipated in the tungsten. The entire assembly, including bellows, occupies approximately 0.6 m of lattice space.

Circulating standard low conductivity water through cooling channels on the outside of the collimator box, can remove 11 kW of DC power from a single collimator. A flow of 2.2 gallons per minute, will remove this power with a temperature rise of 20°C. Further investigations should be done for collimation system efficiency and optimization.

References

[1] C.M. Bhat, P. Martin, and T. Leveling, “Main Injector and Recycler Ring Shielding Assessment”, MI Note-0225, Jan. 14, 1998. C.M. Bhat, P. Martin, and T. Leveling, “Main Injector 8 GeV Beamline Shielding Assessment”, MI Note-0205, Feb. 10, 1997.

[2] S. D. Holmes, "Main Injector Safety Assessment Document," July 1998. R. D. Swain and C.M. Bhat, "A Preliminary Analysis of Ground-Water and Surface-Water Radioactivity Around the Main Injector Extraction and Injection Regions," MI Note-0225, Nov., 1997.

[3] E. A. Sudicky, T. D. Wadsworth, J. B. Kool, and P. S. Huyakorn, "PATCH3D-Three-Dimensional Analytic Solution for Transport in a Finite Thickness Aquifer with First-Type Rectangular Patch Source." Prepared for Woodward Clyde Consultants, HydroGeologic Inc. Herndon, Va., January 1988.

[4] Gary Lauten, Beams Division ES&H Dept., private communication.

[5] Code of Federal Regulations, 10 CFR 835, "Occupational Radiation Protection," current version. *Fermilab Radiological Control Manual current version.*

[6] DOE Order 5400.5, "Radiation Protection of the Public and the Environment," January 1993.

[7] United States Code of Federal Regulations, Title 40, Part 61, Subpart H, "National Emissions Standard for Hazardous Air Pollutants (NESHAP) for the Emission of Radionuclides other than Radon from Department of Energy Facilities," 1989.

[8] Matt Fergusen, Beams Division ES&H Dept, private communication.